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On the non-destructive measurement of local mass transfer using X-ray computed tomography

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ABSTRACT

A novel methodology is developed here to measure wall mass transfer rates non-destructively using X-ray computed tomography (CT). The mass transfer was measured using a gypsum lined 203 mm diameter straight pipe section using a dissolving wall method to water. The measurements were performed at a Reynolds number of 86,000 and Schmidt number of 1200. The local wear of the internal surface is obtained from the CT scans by aligning and analyzing the cross-sectional scanned images of the test section before and after the experiment. The full surface wear contours and the corresponding mass transfer rates are obtained by a three-dimensional reconstruction of the entire test section. The measurements from the CT scans are compared to results obtained from ultrasonic (UT) measurements of the wall thickness and internal surface measurements using a Coordinate Measuring Machine (CMM) and digital laser scans. The results from the CT scan methodology are in good agreement with the other methods, indicating that the method is robust and can be used to obtain the local mass transfer and roughness over the entire surface. Thus, it can be used as a principal method to investigate mass transfer non-intrusively in complex piping geometries.

1. Introduction

Flow Accelerated Corrosion (FAC) causes wall thinning and weakening of carbon steel piping components in power generation plants. If this is not predicted or detected in planned outages, there is the danger of sudden rupture and failure of the piping system. FAC consists of electrochemical reactions at the metal–oxide interface, chemical erosion at the oxide layer and convective mass transfer of the ferrous ions from the oxide–water interface into the bulk flow [1]. The mass transfer rate from the wall to the bulk flow plays a limiting role in the wall thinning rates. Thus, control of FAC in practical applications requires the identification of regions of high local mass transfer in the piping systems.

The mass transfer in piping components has been measured using a variety of methods, including: (i) dissolving wall methods [2–7], (ii) electrochemical techniques [8–11], and (iii) through analogy with heat transfer [12,13]. The advantages and drawbacks of these methods are reviewed in [6]. The drawback of the limiting current density electrochemical technique (LCDT) is that it cannot be used to study the change in mass transfer rates over a dissolving surface. The use of the analogy between heat and mass transfer [12] to infer mass transfer coefficients can be problematic, since most heat transfer measurements are performed at relatively low Prandtl numbers, typically less than 10, while the diffusion of the iron magnetite layer of carbon steel piping in water occurs at a Schmidt number of about 1200. Furthermore, in heat transfer applications there is little change to the surface topography. In mass transfer applications, however, the surface will change with the development of roughness due to the mass transfer, which can significantly affect the mass transfer rates. Dissolving wall methods are well suited in these instances, since the surface roughness will develop due to the flow.

The local wall thinning rates in the dissolving wall method have been measured using ultrasonic transducers (UT) [5,17], Coordinate Measuring Machine (CMM) measurements [7,18], laser scans of the internal surface [19,20] and through X-rays of the test section [5]. Ultrasonic sensors are commonly used for local wall thickness measurements or flaw inspection [14–16], and has been used to measure the local mass transfer rates at selected locations in straight pipes and downstream of an orifice [5,17]. Goldstein and Cho [7] used an automated surface measuring system, akin to a CMM, to measure the mass transfer on a flat surface using

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the naphthalene sublimation method. Yamagata et al. [18] measured the mass transfer downstream of an orifice in a circular pipe by measuring the surface height of a layer of benzoic acid before and after the experiment on two sectioned halves of a test specimen using a CMM. Mazhar et al. [19] and Le et al. [20] measured the local mass transfer and roughness in single and back-to-back bends using gypsum test sections, where the test section was sectioned and the surface topography was obtained by laser scanning of the worn surface.

The objective here is to develop a non-intrusive methodology using X-ray computed tomography (CT) for measurements of the mass transfer and surface roughness. CT has been used for dimensional metrology in other fields, including engineering design and manufacturing for quality control, because it can be used non-destructively to generate high-resolution images for both the internal and external surfaces [21,22]. Wilkin et al. [5] measured the local mass transfer in pipes and elbows by analyzing X-ray photographs of two perpendicular planes on the test section at different run times. This method did appear to be effective but the analysis tools were limited at that time. The CT technique overcomes these difficulties, since it can provide a full 3-dimensional image of the test sections. Experiments were performed for mass transfer using a gypsum lined straight pipe section in water, which provides a Schmidt number of 1200, similar to dissolution of ferrous ions Fe^{2+} in water [10]. The results from the CT scan methodology were compared to those from UT, CMM and laser scans. The experimental facilities and data reduction techniques are presented in the next section, followed by a discussion and presentation of the results and ends with the conclusions of the study.

2. Experimental facility and measurement methodologies

The mass transfer experiments were performed in the test facility shown schematically in Fig. 1. The water in the facility flows from a 1.5 m^3 reservoir through a 101.5 mm diameter, 9 m long downcomer before entering a centrifugal pump at the bottom of the loop. The flow exits the pump to a 203 mm diameter, 9.5 m long acrylic riser through a sudden expansion at the bottom of the riser. The flow passes through the riser with a length of 36 diameters before entering the gypsum lined test section. The flow exits the test section to a 9 diameter long downstream pipe before flowing back into the reservoir. The flow rate was controlled using a pump speed controller and was measured using a Pitot tube in the riser downstream of the test section and an orifice plate (diameter ratio $\beta = 0.6$) installed in the downcomer. The temperature of water throughout the testing time was measured at three locations along the loop: (i) in the riser upstream of the test section, (ii) in the main reservoir and (iii) in the downcomer. The water temperature just upstream of the test section was maintained at 25 ± 0.5 °C using a cooling coil in the reservoir. The electric conductivity of water in the reservoir was measured by a conductivity probe and recorded with a dedicated computer. Calibration tests were performed offline to correlate the concentration of dissolved gypsum to the electric conductivity of the water at 25 °C.

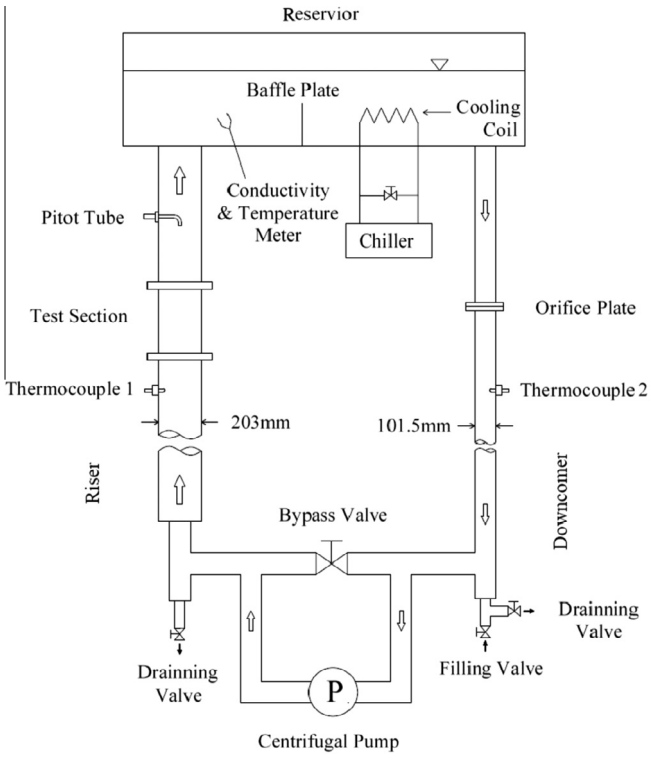

Fig. 1. Schematic of experimental test facility.

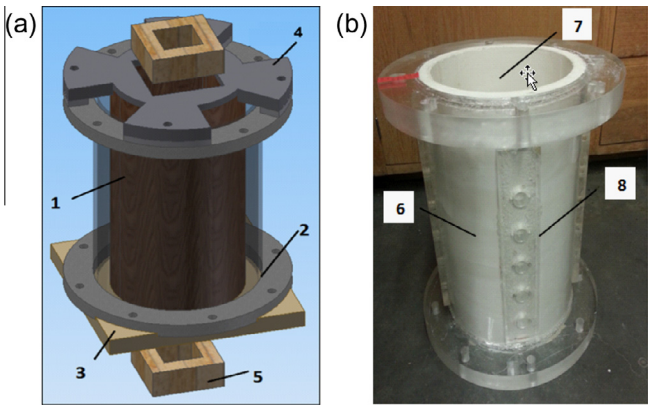

Fig. 2. (a) Assembly of mold for casting the gypsum lining and (b) fabricated test section (1. Inner Core, 2 & 6. Outer Acrylic Casing, 3. Base Plate, 4. End Cap, 5. Wooden Insert, 7. Gypsum Liner, 8. Acylic Strip for UT sensors).

The test section was a gypsum lined straight pipe that was 203 mm in diameter and 406 mm long. The test section was manufactured using a collapsible maple wooden core and an acrylic casing as shown in Fig. 2(a). The wooden core (which forms the inner surface of the test section) has an outer diameter of 203 mm and the acrylic casing has an inner diameter of 235 mm, which leads to a 16 mm thick gypsum liner. Four acrylic strips were machined and glued to the outer casing of the test section shown in Fig. 2(b). Five holes that were equally spaced at 50.8 mm were drilled on each strip to accommodate ultrasonic transducers to measure the thickness of the gypsum lining. The holes along the four acrylic strips was offset by 12.7 mm along the axial direction. The acrylic casing and wooden core were held concentrically during the casting process, using fixtures including the base plate and end cap. The inside of the wooden core was braced with wooden inserts along its length. The gypsum was generated by mixing hydrocal ($CaSO_4 \cdot 1/2H_2O$) with water that yields gypsum with a density of 1580 kg/m^3. A small ratio of citric acid was added during the mixing stage to slow the curing process to facilitate the casting. The casting was left to cure under ambient conditions for approximately 20 days until the weight measured by a scale accurate to ±25 g reached steady state.

The test section was CT scanned before the experiment to obtain the inner surface topography of the unworn gypsum lining. The test section was installed in the riser and water was allowed to flow through the test section at a Reynolds number of 86,000. The experiments were performed for time intervals of 9, 6, 6, 6, 6 h for